

Protease-activated receptor 2 sensitizes TRPV1 by protein kinase C ϵ - and A-dependent mechanisms in rats and mice

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Proteases that are released during inflammation and injury cleave protease-activated receptor 2 (PAR₂) on primary afferent neurons to cause neurogenic inflammation and hyperalgesia. PAR₂-induced thermal hyperalgesia depends on sensitization of transient receptor potential vanilloid receptor 1 (TRPV1), which is gated by capsaicin, protons and noxious heat. However, the signalling mechanisms by which PAR₂ sensitizes TRPV1 are not fully characterized. Using immunofluorescence and confocal microscopy, we observed that PAR₂ was colocalized with protein kinase (PK) C ϵ and PKA in a subset of dorsal root ganglia neurons in rats, and that PAR₂ agonists promoted translocation of PKC ϵ and PKA catalytic subunits from the cytosol to the plasma membrane of cultured neurons and HEK 293 cells. Subcellular fractionation and Western blotting confirmed this redistribution of kinases, which is indicative of activation. Although PAR₂ couples to phospholipase C β , leading to stimulation of PKC, we also observed that PAR₂ agonists increased cAMP generation in neurons and HEK 293 cells, which would activate PKA. PAR₂ agonists enhanced capsaicin-stimulated increases in [Ca²⁺]_i and whole-cell currents in HEK 293 cells, indicating TRPV1 sensitization. The combined intraplantar injection of non-algesic doses of PAR₂ agonist and capsaicin decreased the latency of paw withdrawal to radiant heat in mice, indicative of thermal hyperalgesia. Antagonists of PKC ϵ and PKA prevented sensitization of TRPV1 Ca²⁺ signals and currents in HEK 293 cells, and suppressed thermal hyperalgesia in mice. Thus, PAR₂ activates PKC ϵ and PKA in sensory neurons, and thereby sensitizes TRPV1 to cause thermal hyperalgesia. These mechanisms may underlie inflammatory pain, where multiple proteases are generated and released.

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Protease-activated receptor 2 (PAR₂) is widely expressed in the nervous system where it mediates the actions of proteases on diverse neuronal processes (reviewed in Ossovskaya & Bunnett, 2004). Proteases from the circulation (coagulation factors VIIa, Xa; Camerer *et al.* 2000), inflammatory cells (tryptase; Corvera *et al.* 1997; Molino *et al.* 1997), epithelial cells and neurons (trypsin I, II, IV; Cottrell *et al.* 2004) can cleave PAR₂ to expose a tethered ligand domain that binds to and activates the cleaved receptor. Activated PAR₂ controls neurogenic inflammation, pain and neuronal excitability. PAR₂ is expressed by primary spinal afferent neurons, where activation stimulates release of substance P and

calcitonin gene-related peptide in peripheral tissues to cause neurogenic inflammation (Steinhoff *et al.* 2000; Cenac *et al.* 2002, 2003; Nguyen *et al.* 2003). Similar mechanisms mediate the effects of PAR₂ agonists on airway constriction (Ricciardolo *et al.* 2000) and gastric mucus secretion (Kawabata *et al.* 2001b). PAR₂ agonists also cause thermal and mechanical somatic hyperalgesia (Kawabata *et al.* 2001a; Vergnolle *et al.* 2001), and excite mesenteric sensory neurons to induce visceral hyperalgesia (Hoogerwerf *et al.* 2001; Coelho *et al.* 2002; Kirkup *et al.* 2003). However, the molecular mechanisms by which PAR₂ regulates neuronal functions are incompletely understood.

PAR₂-induced thermal hyperalgesia depends on sensitization of transient potential receptor vanilloid 1 (TRPV1) (Amadesi *et al.* 2004; Dai *et al.* 2004). TRPV1 is a non-selective cation channel expressed by nociceptive neurons, that mediates inflammatory and thermal hyperalgesia (Caterina *et al.* 1997, 2000; Davis *et al.* 2000). Exogenous (capsaicin, ethanol) and endogenous (protons pH < 6.0, heat > 43°C, anandamide) factors directly activate TRPV1 (Caterina *et al.* 1997; Zygmunt *et al.* 1999; Trevisani *et al.* 2002). In addition, PAR₂ agonists (Amadesi *et al.* 2004; Dai *et al.* 2004) and other inflammatory agents, including bradykinin, ATP, prostaglandin E₂ (PGE₂) and nerve growth factor (NGF) (Lopshire & Nicol, 1997; Chuang *et al.* 2001; Tominaga *et al.* 2001; Vellani *et al.* 2001) indirectly sensitize TRPV1, causing hyperalgesia. The mechanisms of this sensitization include activation of protein kinase (PK) C and PKA, which phosphorylate TRPV1 to modify channel gating (Lopshire & Nicol, 1998; Premkumar & Ahern, 2000; Bhawe *et al.* 2002; Mohapatra & Nau, 2003). The PKC ϵ isozyme, which plays a major role in mechanical and thermal hyperalgesia (Khasar *et al.* 1999), phosphorylates TRPV1 (Numazaki *et al.* 2002) to mediate bradykinin-induced sensitization of TRPV1 currents (Cesare *et al.* 1999). PKA, a mediator of injury-induced hyperalgesia (Malmberg *et al.* 1997), also phosphorylates TRPV1 to regulate its desensitization (Bhawe *et al.* 2002; Mohapatra & Nau, 2003), and thereby mediates PGE₂-induced sensitization of TRPV1 (Lopshire & Nicol, 1998; Rathee *et al.* 2002). Additional mechanisms of TRPV1 sensitization include altered interactions of TRPV1 with the endogenous inhibitor phosphatidylinositol-4,5-bisphosphate (Chuang *et al.* 2001; Prescott & Julius, 2003), and PKC- and Src kinase-dependent trafficking of TRPV1 to the plasma membrane (Morenilla-Palao *et al.* 2004; Zhang *et al.* 2005).

The purpose of the present investigation was to define the mechanisms by which PAR₂ sensitizes TRPV1 to induce thermal hyperalgesia. Although PKC ϵ contributes to PAR₂-induced sensitization of TRPV1 currents (Dai *et al.* 2004), the role of PKC ϵ in PAR₂-induced thermal hyperalgesia has not been examined, and the contributions of other second messenger kinases, such as PKA, are unknown. Our objectives were to determine whether (1) primary spinal afferent neurons that express PAR₂ also contain PKC ϵ and PKA, using immunofluorescence and confocal microscopy; (2) PAR₂ agonists activate and cause membrane translocation of PKC ϵ and PKA in neurons and cell lines, using microscopy, subcellular fractionation and Western blotting; (3) PKC ϵ and PKA mediate PAR₂-induced sensitization of TRPV1 in cell lines, by measuring TRPV1 Ca²⁺ signals and currents; and (4) PKC ϵ and PKA mediate PAR₂-induced sensitization of TRPV1-dependent thermal hyperalgesia.

Methods

Animals

Sprague-Dawley rats (male, 200–250 g) and C57Bl6 mice (male, 6–8 weeks) were obtained from Charles River Laboratories (CA, USA, and Canada). The study was approved by Institutional Animal Care and Use Committees of the University of California, San Francisco and the University of Calgary. At the end of the experiments animals were humanely killed using sodium pentobarbital (200 mg kg⁻¹ i.p.) and bilateral thoracotomy.

Agonists and antagonists

PAR₂-activating peptide (PAR₂-AP, SLIGRL-NH₂), corresponding to the tethered ligand of rat and mouse PAR₂, and the inactive reverse peptide sequence (PAR₂-RP), which was used as the control, were obtained from Sigma Genosys (The Woodlands, TX, USA). Bovine pancreatic trypsin was from Worthington Biochemical Corporation (Lakewood, NJ, USA). The selective PKC ϵ translocation inhibitor peptide (EAVSLKPT, PKC ϵ I), inactive scrambled sequence (PKC ϵ I-sc), the PKA inhibitor H-89 (N-[2-((*p*-bromocinnamyl)amino)ethyl]-5-isoquinolinesulphonamide), cell-permeable myristoylated PKA inhibitor 14–22 amide (PKAI_{14–22}, Myr-GRTGRRNAI-NH₂), and the PKA activator forskolin were from Calbiochem (La Jolla, CA, USA). The PKC activators phorbol 12-myristate 13-acetate (PMA) and phorbol dibutyrate, and indomethacin, a cyclo-oxygenase inhibitor, were from Sigma (St Louis, MO, USA). The PKA inhibitor WIPTIDE (TTYADFIASGRTGRRNAI-NH₂) was from Peninsula Laboratories (San Carlos, CA, USA). The PKC ϵ I conjugated to TAT protein to promote membrane permeability (Schwarze *et al.* 1999) (TAT-PKC ϵ I, YGRKKRRQRRRC-disulphide bond-CEAVSLKPT-COOH) and the inactive scrambled sequence (TAT-PKC ϵ I-sc) were from SynPep Corp (Dublin, CA, USA). The selection of inhibitors and doses used in this study was based on previous studies (Aley *et al.* 2000, 2001; Hu *et al.* 2002; Rathee *et al.* 2002).

Antibodies

Rabbit anti-human PKC ϵ , rabbit anti-human PKA α catalytic subunit (PKA_C), mouse anti-human PAR₂ (SAM11) and mouse anti-EGFP (enhanced green fluorescent protein) were from Santa Cruz Biotechnology, Inc. (Santa Cruz, CA, USA). Goat anti-rabbit and anti-mouse IgG conjugated to FITC, Rhodamine Red X or horseradish peroxidase were from Jackson ImmunoResearch (West Grove, PA, USA). In control experiments,

primary antibodies were incubated before use with peptides used for immunization (1 μ M, 24 h, 4°C).

Cell lines

Human embryonic kidney (HEK) 293 cells were maintained in modified Eagle's with Earle's BSS medium (MEM), 10% fetal bovine serum (FBS) and 100 U ml⁻¹ penicillin, 0.1 mg ml⁻¹ streptomycin. HEK 293 cells stably expressing human TRPV1 (HEK-TRPV1, a gift from Dr J. Davis, GSK Harlow, UK) were generated and maintained in MEM, 10% FBS and geneticin (400 mg l⁻¹) (Hayes *et al.* 2000). HEK-FLP cells (Invitrogen, Carlsbad, CA, USA) stably expressing human PAR₂ with N-terminal Flag and C-terminal T7 epitopes (HEK-PAR₂) were generated and maintained as described (Jacob *et al.* 2005). HEK 293 cells were transiently transfected with 1 μ g of EGFP-human PKC ϵ (a gift from Dr Daria Mochly Rosen, Stanford University) using Lipofectamine 2000 (Invitrogen) to generate HEK-PKC ϵ -EGFP cells (Schechtman *et al.* 2004). These cells were studied 48 h after transfection.

Neuronal culture

Rats were anaesthetized with sodium pentobarbital (200 mg kg⁻¹ i.p.). Dorsal root ganglia (DRG) from the thoracic and lumbar spinal cord were removed and minced in cold Hank's balanced salt solution (HBSS) and incubated for 60–90 min at 37°C in Dulbecco's modified Eagle's medium (DMEM) containing 0.5 mg ml⁻¹ of trypsin, 1 mg ml⁻¹ of collagenase type IA and 0.1 mg ml⁻¹ of DNase type IV (Sigma) (Steinhoff *et al.* 2000). Soybean trypsin inhibitor (Sigma) was added to neutralize trypsin. Neurons were pelleted, suspended in DMEM containing 10% FBS, 10% horse serum, 100 U ml⁻¹ penicillin, 0.1 mg ml⁻¹ streptomycin, 2 mM glutamine and 2.5 μ g ml⁻¹ DNase type IV, plated on glass coverslips coated with Matrigel (BD Biosciences, Bedford, MA, USA), and cultured for 2–3 days.

Localization of PKC ϵ and PKA ζ in cultured cells

HEK 293 cells and cultured DRG neurons were incubated in HBSS, 0.1% BSA, 20 mM Hepes, pH 7.4 at 37°C and treated with test substances. Cells were fixed with 4% paraformaldehyde, 100 mM PBS, pH 7.4 for 20 min at 4°C. Cultured cells were incubated with PBS containing 5–10% normal goat serum and 0.1–0.3% Triton X-100 for 30 min, and incubated with primary antibodies to PKC ϵ (1 : 250) or PKA ζ (1 : 400) for 16 h at 4°C. After washing, cells were incubated with goat anti-rabbit IgG conjugated to FITC (1 : 300) for 2 h at room temperature. Cells expressing PKC ϵ -EGFP were similarly treated and fixed.

Localization of PKC ϵ , PKA ζ and PAR₂ in DRG sections

Rats (male, 200 g) were anaesthetized with sodium pentobarbital (200 mg kg⁻¹ i.p.) and transcardially perfused with PBS containing 100 U of heparin, followed by 4% paraformaldehyde in 100 mM PBS, pH 7.4. DRG (L4–L6) were immersion fixed for 4 h at 4°C. DRG were incubated in 20% sucrose in PBS for 24 h at 4°C, embedded in OCT compound (Miles, Elkhart, IN, USA), and frozen sections of 16 μ m were prepared. Sections were incubated with PBS containing 5–10% normal goat serum and 0.1–0.3% Triton X-100 for 30 min, and incubated with primary antibodies: PKC ϵ (1 : 750), PKA ζ (1 : 750), PAR₂ (1 : 250) for 16 h at 4°C. After washing, sections were incubated with goat anti-rabbit IgG conjugated to FITC or goat anti-mouse IgG conjugated to Rhodamine Red X (1 : 200) for 2 h at room temperature. Slides were washed and mounted in Prolong (Molecular Probes, Eugene, OR, USA).

Confocal microscopy

Specimens were observed using Zeiss Axiovert and Bio-Rad MRC1000 confocal microscopes with Zeiss Plan Apo \times 40 (NA 1.4) or \times 100 (NA 1.3) objectives. Images were collected at zoom of 1–2, iris of < 3 μ m and typically 5–10 optical sections were taken at intervals of 0.5 μ m. Images were coloured to represent the appropriate fluorophores, and processed using Adobe Photoshop 7.0 (Adobe Systems, Mountain View, CA, USA) to adjust contrast and brightness. Images of stained and control slides were collected and processed identically. To quantify the effects of agonists on the subcellular distribution of PKC ϵ and PKA ζ in cultured neurons, the fluorescence intensity of the cells was measured by selecting a straight line across the neuronal soma and using the plot profile function of ImageJ software (version 10.2, NIH image). The averaged fluorescence intensities between peripheral and central regions of the cell were compared. The number of neurons showing redistribution of these kinases between the cytosol and periphery of the cells was also determined and expressed as a percentage of the total number of neurons analysed.

Subcellular fractionation and Western blotting

HEK 293 cells were maintained overnight in MEM and 0.1% BSA. Cells were incubated in HBSS, 0.1% BSA, 20 mM Hepes, pH 7.4 and treated at 37°C for 0–10 min with PAR₂ agonists. Cells were washed with ice-cold PBS, scraped into 150 μ l of homogenization buffer (20 mM Tris-HCl, pH 7.4 and protease inhibitors) and disrupted with 20 strokes in a glass homogenizer. The lysate was centrifuged at 500 g for 10 min, and the resulting supernatant was centrifuged at 100 000 g for 1 h. The

supernatant was collected as the cytosolic fraction. The pellet containing the membrane fraction was treated with lysis buffer (1% SDS, 20 mM Tris-HCl, pH 7.4 and protease inhibitor cocktail, Roche Diagnostics, Indianapolis, IN, USA). Both cytosolic and membrane fractions were boiled for 5 min and clarified by centrifugation at 15 000 g for 15 min. Protein concentration was measured by BCA assay. Samples (5 µg protein) were separated by SDS-PAGE (8% for PKC ϵ , 12% for PKA $_C$). Proteins were transferred to PVDF membranes (Millipore, Billerica, MA, USA). Membranes were incubated overnight at 4°C with antibodies to PKC ϵ (1 : 10 000), PKA $_C$ (1 : 10 000) or EGFP (1 : 10 000) in PBS containing 5% milk powder, 2% BSA, 0.1% Tween-20. Membranes were washed and incubated with goat anti-rabbit or anti-mouse horseradish peroxidase (1 : 10 000) for 1 h at room temperature. Immunoreactive proteins were detected by Enhanced Chemiluminescence (Pierce, Rockford, IL, USA). To ensure equal loading, membranes were stained with amido-black to detect all proteins.

Measurement of intracellular calcium concentration ([Ca²⁺]_i)

The experimental procedure has been previously described (Amadesi *et al.* 2004). HEK 293 cells were incubated in HBSS, 0.1% BSA, 20 mM Hepes, pH 7.4, containing 2.5 µM of fura-2/AM (Invitrogen) for 30–45 min at 37°C. Coverslips were mounted in an open chamber (350 µl) at 37°C. Fluorescence of individual cells was measured at 340 nm and 380 nm excitation and 510 nm emission using a Zeiss Axiovert microscope, an ICCD video camera (Stanford Photonics, Stanford, CA, USA) and a video microscopy acquisition program (Axon Instruments, Inc., Union City, CA, USA). Test substances were directly added to the chamber (50 µl injection). Each coverslip received only one treatment with PAR₂-AP or RP followed by capsaicin. In some experiments cells were pretreated for 30 min at 37°C with inhibitors before challenging with test substances. The magnitude of capsaicin responses was calculated as the increase above baseline. Results were first calculated as the 340 nm/380 nm emission ratio, which is proportional to the [Ca²⁺]_i, and then expressed as a percentage of the potentiation observed in cells pretreated with PAR₂-AP and antagonist vehicle (100%).

Measurement of intracellular cAMP

HEK 293 cells were maintained overnight in MEM-0.1% BSA. HEK 293 cells and DRG neurons in culture were incubated in HBSS, 0.1% BSA, 20 mM Hepes, pH 7.4 and treated with PAR₂ agonists for 0–5 min at 37°C. Intracellular cAMP levels were measured using the cAMP enzyme immunoassay system following the

non-acetylation protocol according to the manufacturer's directions (Amersham Bioscience, Bucks, UK).

Electrophysiology

The experimental procedure has been previously described (Amadesi *et al.* 2004) with slight modifications. Membrane currents of HEK 293 cells were recorded using an Axopatch 1D amplifier (Axon Instruments). Patch pipette resistance ranged from 1 to 3 MΩ, and the holding potential was –60 mV. The pipette solution was (mM): KCl 140, MgCl₂ 1, EGTA 5, Hepes 5, and ATPNa₂ 5. The external solution was (mM): NaCl 140, CaCl₂ 2, KCl 4, MgCl₂ 1, glucose 11, Hepes 5 and CsCl 3. The pH was adjusted with either KOH (pipette solution, pH 7.2) or NaOH (external solution, pH 7.4). In these standard solutions the input resistance of the HEK 293 cells was 1–10 GΩ. Whole-cell currents were recorded using Axotape software and analysed using Axograph software (Axon Instruments). Membrane potentials were corrected for the liquid junction potential (pipette –11 mV). The recording chamber was continuously superfused with the external solution at approximately 2 ml min^{–1}. Rapid application of agonists in the external solution was made using an eight-barrelled fast-flow device (Barajas-Lopez *et al.* 1994). Experiments were at room temperature (~23°C). Control TRPV1 responses were obtained by repeated application of capsaicin (300 nM) for ~20 s. Only neurons that did not exhibit desensitization to two consecutive capsaicin applications were selected for the study. PAR₂-AP (100 µM) or, in a small series of experiments, the PKC agonist phorbol dibutyrate (300 nM) was then applied for 2 min and TRPV1 responses were examined at 30 s to 18 min following PAR₂ activation. Results were expressed as a percentage of the control TRPV1 current. In some experiments, PKC ϵ translocation inhibitor peptide or H89 was added to the pipette solution.

Paw withdrawal latency

Test substances were administered by intraplantar injection in mice under light halothane (5%) anaesthesia (Vergnolle *et al.* 2001). PAR₂-AP, PAR₂-RP, PKC ϵ and PKA inhibitors were dissolved in physiological saline (0.9% NaCl); capsaicin was dissolved in 80% physiological saline, 10% ethanol, and 10% Tween 80. To allow the entry of the membrane-impermeant inhibitors into cells, injection of PKC ϵ I, PKC ϵ I-sc and WIPTIDE (all 2.5 µl paw^{–1}) was preceded by injection of distilled water (2.5 µl paw^{–1}) to cause a transient hyposmotic permeabilization. Mice received an intraplantar injection of PAR₂-AP and capsaicin (5 µl paw^{–1}) 15–30 min later (final volume 10 µl paw^{–1}). The latency of paw withdrawal to a radiant heat stimulus was measured before and after

the intraplantar injections of test substances, using a plantar test apparatus (Ugo Basile, Milan, Italy). Thermal hyperalgesia was defined as a decrease in the withdrawal latency compared to the basal measurement.

Statistical analysis

Results are expressed as mean \pm s.e.m. Comparisons between groups were made by ANOVA and the Bonferroni test, Student's *t* test, or a paired Student's *t* test to evaluate differences between the same cells. Comparisons between proportions were made using Primer of Biostatistics software (3.1 version, Macintosh version, McGraw Hill, 1992) and the 'standard error of proportion' and the 'compare two proportions' functions. Differences were considered significant when $P \leq 0.05$.

Results

DRG neurons that express PAR₂ also contain PKC ϵ and PKA_C

PAR₂ is present in DRG neurons that express substance P, calcitonin gene-related peptide and TRPV1, and which therefore mediate neurogenic inflammation and nociception (Steinhoff *et al.* 2000; Amadesi *et al.* 2004). To determine if PAR₂-expressing neurons also contain the potential regulatory kinases PKC ϵ and PKA_C, we used immunofluorescence. Immunoreactive PAR₂ was present in small- and medium-diameter neurons that are typically considered nociceptive neurons (Fig. 1A and D). These neurons also contained immunoreactive PKC ϵ and PKA_C (Fig. 1B, C, E and F, arrows). Staining for PKC ϵ and PKA_C was abolished by preabsorption of the antibodies with the peptides used for immunization, suggesting specificity

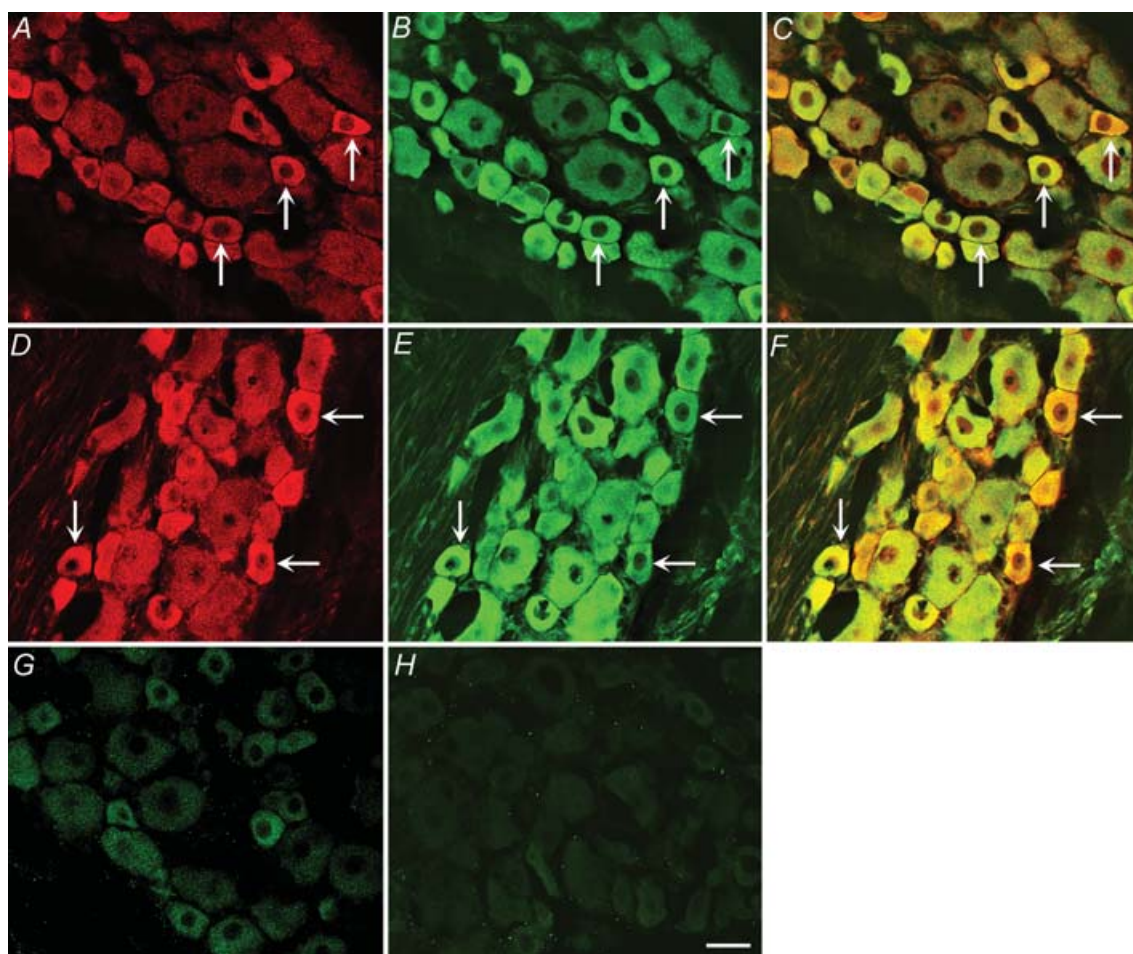


Figure 1. Localization of immunoreactive PAR₂, PKC ϵ and PKA_C in DRG neurons

A and D, PAR₂; B, PKC ϵ ; E, PKA_C; C and F, merge. G, PKC ϵ preabsorption control; H, PKA_C preabsorption control. Neurons expressing PAR₂ also expressed PKC ϵ and PKA_C (arrows). Scale bar = 20 μ m.

(Fig. 1G and H). Since PAR₂ and TRPV1 are coexpressed in nociceptive neurons (Amadesi *et al.* 2004), PKC ϵ and PKA_C are appropriately localized to mediate PAR₂-induced regulation of TRPV1.

PAR₂ agonists activate PKC ϵ in HEK 293 cells and DRG neurons

PKC ϵ phosphorylates and sensitizes TRPV1 (Numazaki *et al.* 2002). We investigated the effects of PAR₂ agonists on translocation of PKC ϵ from the cytosol to the plasma membrane, since membrane translocation of PKC ϵ is an index of activation of this kinase (Dorn & Mochly Rosen, 2002). We first studied trafficking of PKC ϵ -EGFP expressed in HEK 293 cells, which can be detected with high sensitivity and specificity. PAR₂ agonists sensitize TRPV1 similarly in HEK 293 cells and DRG neurons (Amadesi *et al.* 2004). Thus, HEK 293 cells, which naturally express PAR₂, are a useful model system to study regulation of TRPV1. In unstimulated HEK 293 cells, PKC ϵ -EGFP was detected in the cytosol (Fig. 2A). PMA (1 μ M), a PKC activator, induced a prominent redistribution of PKC ϵ -EGFP from the cytosol to the plasma membrane at 5 min (Fig. 2A). In a similar manner, PAR₂-AP (100 μ M) induced trafficking of PKC ϵ -EGFP to the membrane within 0.5 min and 1 min (Fig. 2A), and after 15 min PKC ϵ -EGFP returned to the cytosol (results not shown). PAR₂-RP (100 μ M, 1 min) did not affect the subcellular distribution of PKC ϵ -EGFP (Fig. 2A). PMA and PAR₂-AP also stimulated membrane translocation of immunoreactive PKC ϵ in HEK-TRPV1 cells (results not shown). Thus, EGFP does not interfere with the redistribution of PKC ϵ to the plasma membrane. Of note, PAR₂-AP also caused translocation of PKC ϵ -EGFP to the nucleus after 1 min (Fig. 2A). However, we did not detect nuclear translocation of endogenous PKC ϵ after exposure to PAR₂-AP (not shown). Thus, the physiological relevance of this redistribution is unknown.

We also examined the effects of PMA and PAR₂ agonists on the subcellular localization of immunoreactive PKC ϵ in rat DRG neurons in culture. Since the effects of agonists on PKC ϵ trafficking in neurons were less prominent than in HEK 293 cells, we measured the pixel intensity of signals in the central (cytosol) and peripheral (membrane) regions of the soma, and also determined the proportion of neurons in which there was detectable redistribution of PKC ϵ . In unstimulated neurons, immunoreactive PKC ϵ was predominantly diffusely localized in the cytosol (Fig. 2B). The PKC ϵ signal was most intense in the cytosol, with minimal signal at the plasma membrane (Fig. 2C). Indeed, PKC ϵ was detected at the plasma membrane of only $3 \pm 5\%$ of the unstimulated neurons ($n = 318$ total neurons) (Fig. 2D). PMA (1 μ M, 5 min) induced a prominent redistribution of PKC ϵ from the cytosol

to the plasma membrane of neurons (Fig. 2B and C), and now membrane staining was detected in $99 \pm 2\%$ of neurons ($n = 176$) (Fig. 2D). PAR₂-AP (100 μ M) also induced trafficking of PKC ϵ to the plasma membrane within 0.5 min ($14 \pm 4\%$ of $n = 196$), with a maximal effect at 1 min ($62 \pm 3\%$ of $n = 125$) (Fig. 2B–D). At 5 min, PKC ϵ was still localized at the membrane ($77 \pm 5\%$ of $n = 142$), but the staining was more diffuse, suggesting return to the cytosol (not shown). PAR₂-RP (100 μ M) had no effect on the localization of PKC ϵ , with $< 15\%$ of neurons having detectable PKC ϵ at the plasma membrane ($9 \pm 3\%$ of $n = 104$ at 0.5 min and $12 \pm 3\%$ of $n = 152$ at 1 min) (Fig. 2B–D).

To confirm that PAR₂ activation induces membrane translocation of PKC ϵ in HEK 293 cells, and to determine the kinetics of this process, we quantified PKC ϵ in cytosolic and membrane fractions by Western blotting. In unstimulated HEK-PKC ϵ -EGFP cells, PKC ϵ -EGFP was predominantly in cytosolic fractions (Fig. 3A and B). After incubation with PAR₂-AP (100 μ M), the level of PKC ϵ -EGFP increased in membrane fractions and diminished in cytosolic fractions within 0.5–1 min (Fig. 3A and B). PAR₂-AP also caused translocation of endogenous immunoreactive PKC ϵ from cytosolic to membrane fractions of HEK-TRPV1 cells within 1 min (Fig. 3C and D). PKC ϵ -EGFP was still detected in membrane fractions 10 min after PAR₂ activation, when endogenous PKC ϵ had returned to the cytosol. The more persistent presence of PKC ϵ -EGFP in membrane fractions may reflect the higher sensitivity of detection of PKC ϵ -EGFP, or be due to the over-expression of PKC ϵ , or be related to an effect of EGFP on association of PKC ϵ with the membrane. Trypsin (10 nM) caused a similar membrane translocation of PKC ϵ -EGFP and immunoreactive PKC ϵ in HEK 293 cells (not shown). We did not quantify membrane translocation of PKC ϵ in DRG neurons by Western blotting, due to the limited number of cells and the low levels of PKC ϵ expression. Together, our results show that agonists of PAR₂ induce redistribution of PKC ϵ to the plasma membrane in both HEK 293 cells and DRG neurons, suggesting activation of PKC ϵ .

PAR₂ agonists activate PKA in DRG neurons and HEK 293 cells

TRPV1 has been proposed as a target for the cAMP/PKA cascade, and PKA phosphorylates TRPV1 to regulate its desensitization (Bhave *et al.* 2002; Rathee *et al.* 2002). Exposure of sensory neurons to forskolin, which activates the cAMP/PKA cascade, induces translocation of the PKA_C to the cell periphery, which is indicative of activation (Rathee *et al.* 2002). To determine if PAR₂ agonists activate PKA, we examined their effects on the subcellular distribution of PKA_C in DRG neurons. In most

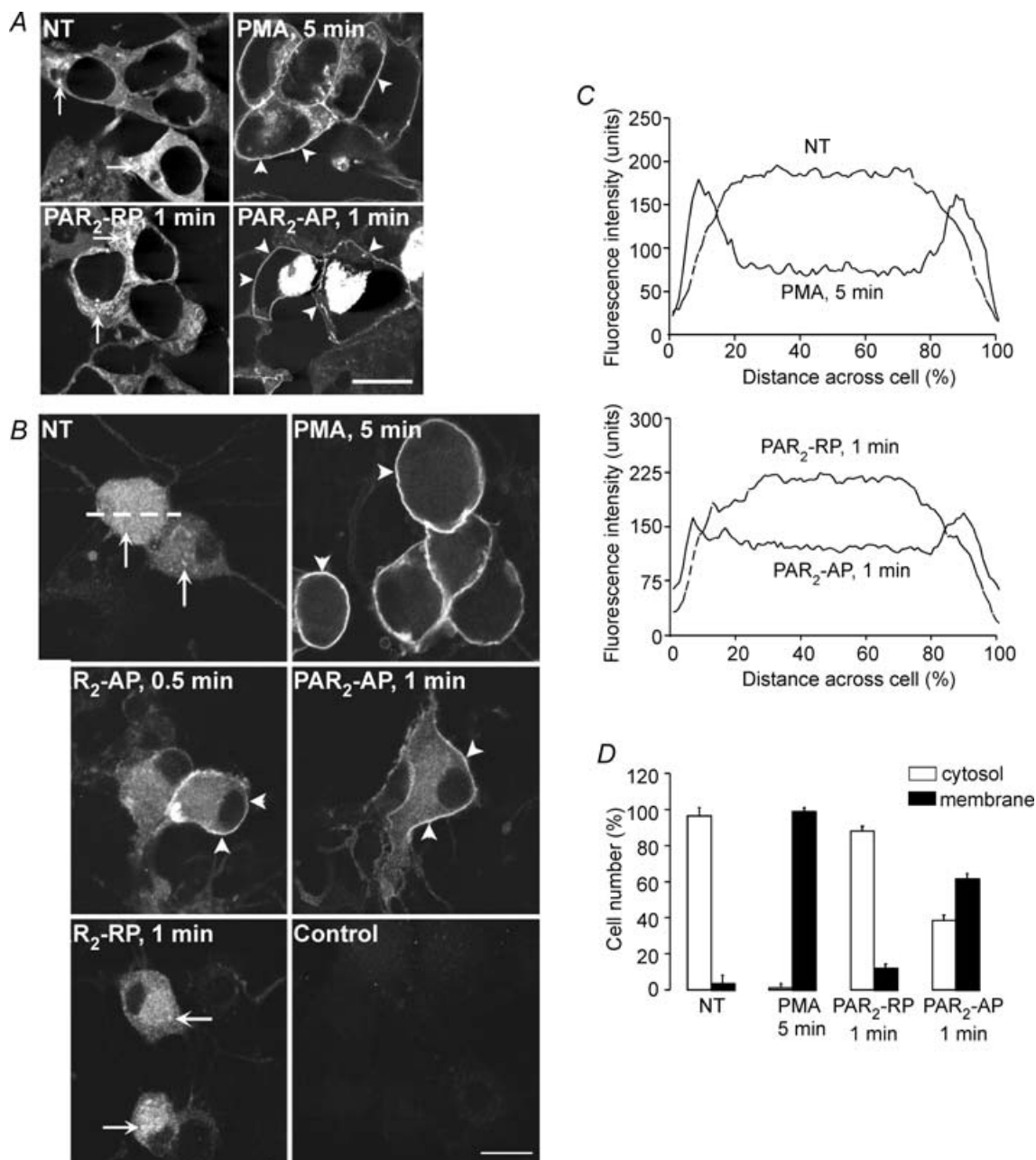


Figure 2. Effects of PAR₂ agonist on the subcellular distribution of PKC ϵ determined by confocal microscopy

A, HEK 293 cells expressing PKC ϵ -EGFP (enhanced green fluorescent protein). In unstimulated cells (non-treated, NT), PKC ϵ -EGFP was cytosolic and in vesicles (arrows). PMA (phorbol 12-myristate 13-acetate) induced translocation to the plasma membrane at 5 min (arrowheads). PAR₂-AP induced translocation to the plasma membrane at 1 min (arrowheads). PAR₂-RP did not affect the subcellular location of PKC ϵ -EGFP, which remained in the cytosol and vesicles (arrows). Scale bar = 10 μ m. **B**, rat DRG neurons in culture. In unstimulated neurons (NT, non-treated), PKC ϵ was cytosolic and in vesicles (arrows). PMA induced translocation of PKC ϵ to the plasma membrane at 5 min (arrowheads). PAR₂-AP also induced translocation of PKC ϵ to the plasma membrane at 0.5 and 1 min (arrowheads). PKC ϵ was in the cytosol and vesicles of cells treated with PAR₂-RP (arrows). Control shows staining with preabsorbed PKC ϵ antibody. Scale bar = 10 μ m. **C**, fluorescence intensity (in arbitrary units) measured in a line bisecting the neuronal soma (e.g. see dashed line in **B**). In untreated cells (NT) or cells incubated with PAR₂-RP (1 min), the signal was mostly cytosolic. In cells treated with PMA (5 min) or PAR₂-AP (1 min), the signal in the cytosol diminished and was more prominent at the plasma membrane. Each trace is an average of 4–6 cells. **D**, the effect of PMA, PAR₂-AP and PAR₂-RP on the percentage of the total number of observed neurons expressing PKC ϵ with PKC ϵ either in the cytosol or at the plasma membrane of the soma. The proportion of cells with PKC ϵ at the plasma membrane was increased after treatment with PMA and PAR₂-AP. Observations from $n > 100$ cells.

unstimulated neurons, immunoreactive PKA_C was cytosolic or present in vesicles that were uniformly distributed throughout the cytoplasm (Fig. 4A). This uniform cytosolic distribution of PKA_C was confirmed by measuring the pixel intensity (Fig. 4B). Indeed, PKA_C was detected in the vicinity of the plasma membrane in only $22 \pm 5\%$ of unstimulated neurons (of $n = 270$ total neurons) (Fig. 4C). Forskolin ($10 \mu\text{M}$, 0.5 min), which activates PKA, stimulated the redistribution of PKA_C from the central to the peripheral region of the cell (Fig. 4A). This redistribution was confirmed by measurement of the pixel intensity of immunoreactive PKA_C (Fig. 4B). This peripheral staining of PKA_C was detected in $92 \pm 2\%$ of neurons ($n = 141$) (Fig. 4C). PAR₂-AP ($100 \mu\text{M}$) also stimulated the redistribution of PKA_C from the central to the peripheral regions of the soma, and this effect was observed in $70 \pm 4\%$ of neurons at 1 min ($n = 143$), and $76 \pm 3\%$ of neurons at 5 min ($n = 205$) after stimulation (Fig. 4A–C). After 10–15 min, PKA_C returned to cytosolic vesicles (not shown). In contrast, PAR₂-RP had no effect on the subcellular distribution of immunoreactive PKA_C, with only $15 \pm 4\%$ of neurons showing localization of PKA_C close to the plasma membrane at 5 min ($n = 106$) (Fig. 4A–C).

To confirm that PAR₂ activation induces membrane translocation of PKA_C in HEK-TRPV1 cells, which endogenously express PKA regulatory and catalytic subunits

(Rathee *et al.* 2002), we quantified PKA_C in cytosolic and membrane fractions by Western blotting. After 1 min of incubation with PAR₂-AP ($100 \mu\text{M}$), there were elevated levels of PKA_C in membrane fractions, and diminished levels in cytosolic fractions (Fig. 5A and B). Thus, PAR₂ agonists cause translocation of PKA_C from the cytosol to membrane fractions, which is indicative of activation of PKA.

It is well established that PAR₂ couples to $G_{\alpha q/11}$, resulting in activation of phospholipase C β and formation of inositol trisphosphate and diacylglycerol, which mobilize intracellular Ca^{2+} ions and activate PKC. However, PAR₂ agonists elevate cAMP levels in keratinocytes (Scott *et al.* 2003), which suggests that PAR₂ may activate the PKA cascade. Therefore, we determined the effects of PAR₂ agonists on cAMP levels in HEK-PAR₂ cells and DRG neurons. PAR₂-AP ($100 \mu\text{M}$) and trypsin (10 nM) increased the cAMP levels in HEK-PAR₂ cells by $\sim 35\%$ within 1 and 5 min, whereas PAR₂-RP ($100 \mu\text{M}$) had no effect (Fig. 5C). Similarly, PAR₂-AP ($100 \mu\text{M}$) and trypsin (10 nM) increased the cAMP levels in rat DRG neurons by 40–60% after 5 min, whereas PAR₂-RP was inactive (Fig. 5C). PAR₂ agonists caused a similar increase of cAMP level in HEK-TRPV1 cells (not shown). Since PAR₂ agonists can stimulate the generation of prostaglandins (Kong *et al.* 1997), which could activate receptors that couple to form cAMP, we determined

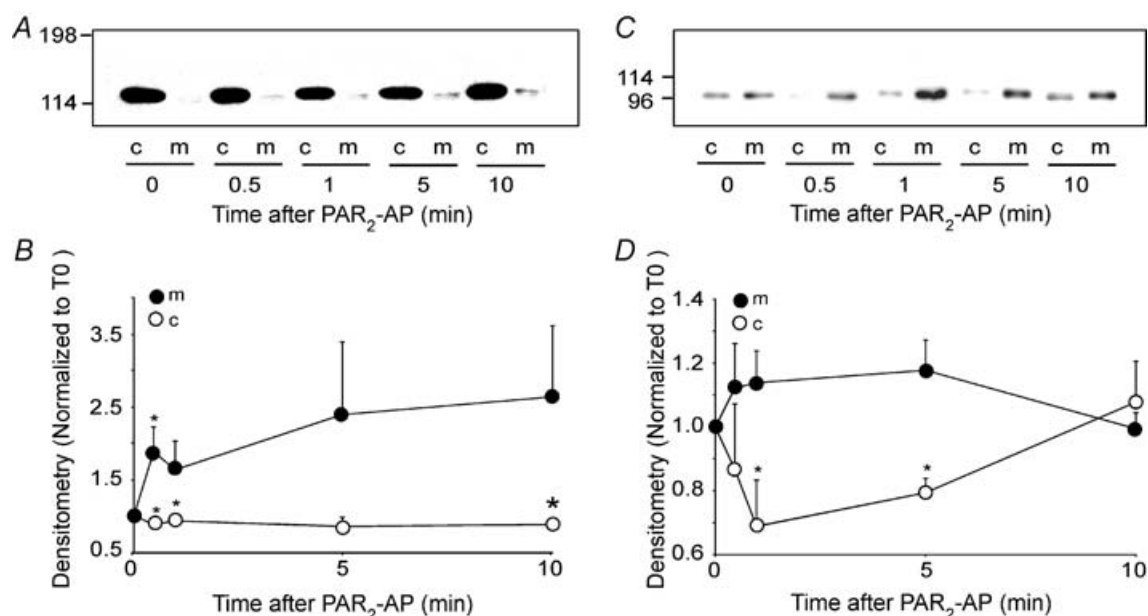


Figure 3. Effects of PAR₂ agonist on the subcellular distribution of PKC ϵ in HEK 293 cells determined by subcellular fractionation and Western blotting

A, Western blot, and B, densitometric analysis of PKC ϵ -EGFP (enhanced green fluorescent protein) in cytosolic (c) and membrane (m) fractions of HEK-PKC ϵ -EGFP cells. PAR₂-AP increased PKC ϵ -EGFP in membrane fractions and decreased PKC ϵ -EGFP in cytosolic fractions. C, Western blot, and D, densitometric analysis of immunoreactive PKC ϵ in cytosolic and membrane fractions of HEK-TRPV1 cells. PAR₂-AP increased PKC ϵ in membrane fractions and decreased PKC ϵ in cytosolic fractions. * $P < 0.05$ compared to 0 min, $n = 4$ experiments.

whether inhibitors of cyclo-oxygenase prevented the effects of PAR₂ agonists on cAMP levels. Indomethacin (5 μ M) did not affect PAR₂-AP or trypsin-stimulated formation of cAMP in HEK 293 cells (not shown). Thus, agonists of PAR₂ induce redistribution of PKA_C and increase cAMP levels in neurons and cells, suggesting an activation of the cAMP/PKA cascade.

PAR₂ agonists sensitize TRPV1-mediated Ca²⁺ responses and TRPV1 currents by PKC ϵ - and PKA-dependent mechanisms

We have previously reported that PAR₂ agonists sensitize TRPV1 Ca²⁺ signals and currents in HEK 293 cells and DRG neurons by mechanisms that require activation of

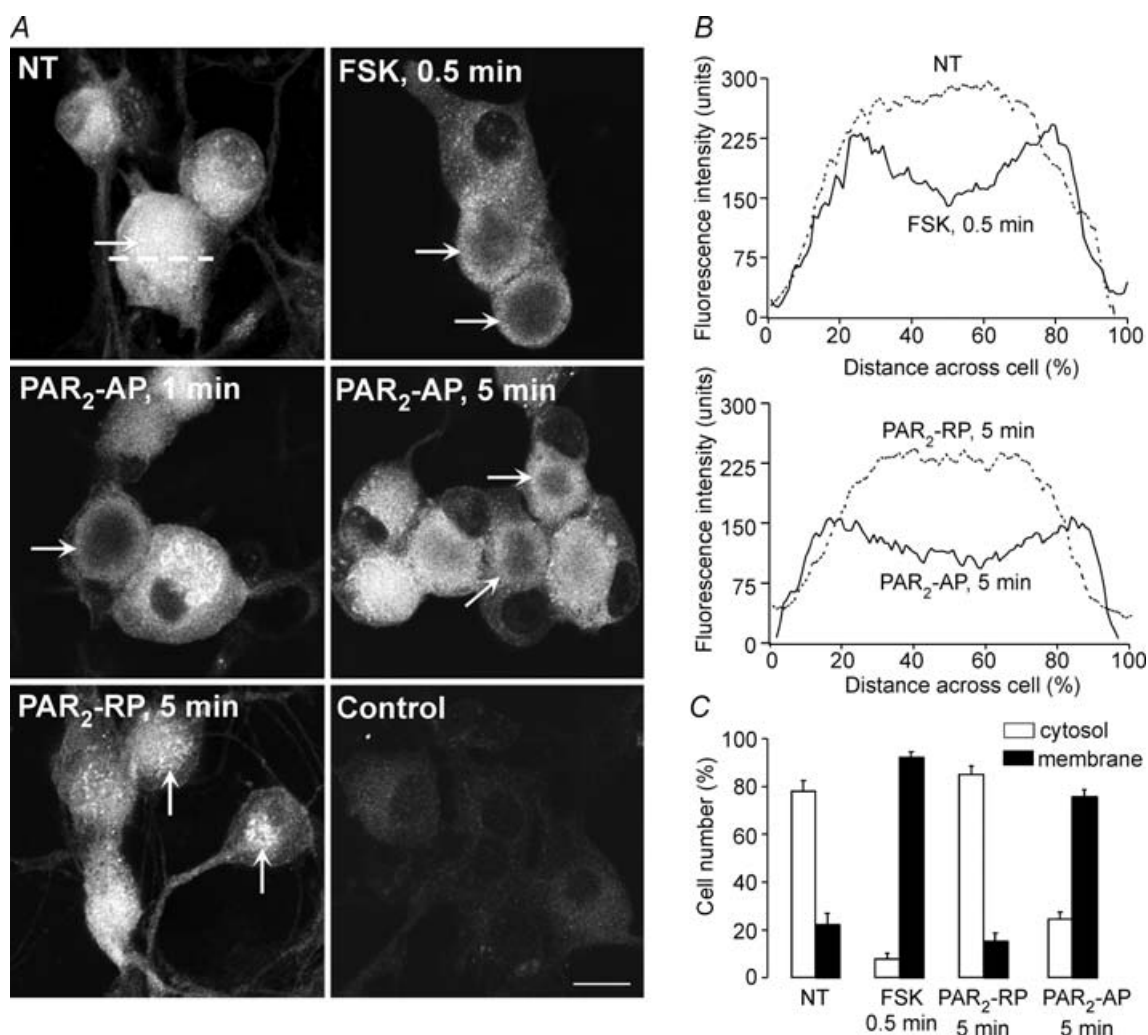


Figure 4. Effects of PAR₂ agonist on the subcellular distribution of PKA_C determined by confocal microscopy in rat DRG neurons in culture

A, unstimulated neuron (non-treated, NT), PKA_C (PKA catalytic subunit) was in vesicles and uniformly distributed throughout the cytosol (arrows). Forskolin (FSK) induced redistribution of PKA_C from the central to the peripheral region of the soma at 0.5 min (arrows). PAR₂-AP also induced redistribution of PKA_C to the peripheral region of the cell at 1 min and 5 min (arrows). PKA_C was uniformly distributed in the cytosol and in vesicles of cells treated with PAR₂-RP (arrows). Control shows staining with preabsorbed PKA_C antibody. Scale bar = 10 μ m. B, fluorescence intensity (in arbitrary units) measured in a line bisecting the neuronal soma (e.g. see dashed line in A). In untreated cells (NT) or cells incubated with PAR₂-RP (5 min), the signal was mostly cytosolic. In cells treated with FSK (0.5 min) or PAR₂-AP (5 min), the signal in the cytosol diminished and was more prominent in superficial regions of the soma. Each trace is an average of 4–6 cells. C, the effects of FSK, PAR₂-AP and PAR₂-RP on the percentage of the total number of observed neurons expressing PKA_C with PKA_C either in the cytosol or near the plasma membrane of the soma. The proportion of cells with PKA in a superficial region of the cytosol was increased after treatment with FSK and PAR₂-AP. Observations from $n > 100$ cells.

phospholipase $C\beta$ and PKC (Amadesi *et al.* 2004). We now used selective inhibitors of PKC ϵ and of PKA to determine their contributions to PAR $_2$ -induced sensitization of TRPV1. HEK-TRPV1 cells were used for these experiments in view of the similar effects of PAR $_2$ agonists on activation of PKC ϵ and PKA and sensitization of TRPV1 in both HEK 293 cells and DRG neurons (Amadesi *et al.* 2004).

Exposure of HEK-TRPV1 cells to PAR $_2$ -AP (100 μ M, 5 min) potentiated the effects of capsaicin (10 nM) on $[Ca^{2+}]_i$ by $\sim 70\%$ ($n = 131$ cells), indicative of TRPV1 sensitization (Fig. 6A and B). In contrast, PAR $_2$ -RP

(100 μ M, 5 min) had no effect. Pretreatment with TAT-PKC ϵ I (10 μ M) prevented this sensitization (Fig. 6B). Thus, the effect of capsaicin in cells treated with TAT-PKC ϵ I and PAR $_2$ -AP was $56 \pm 7\%$ ($n = 116$ cells) of the responses in cells treated with PAR $_2$ -AP and vehicle (100%). Pretreatment with inactive TAT-PKC ϵ I-sc (10 μ M) had no effect on PAR $_2$ -AP-induced sensitization of TRPV1 ($n = 110$ cells). Pretreatment with two selective inhibitors of PKA, H-89 (10 μ M) and the cell-permeable PKAI $_{14-22}$ (0.1 μ M), also prevented PAR $_2$ -AP-mediated sensitization of TRPV1 (Fig. 6B). The effect of capsaicin in cells treated with H-89 and PAR $_2$ -AP was $62 \pm 11\%$, and in cells treated with PKAI $_{14-22}$ and PAR $_2$ -AP was $53 \pm 4\%$ of the responses of cells treated with PAR $_2$ -AP and vehicle (100%) (both $n > 100$ cells). Together, these results suggest that activation of PAR $_2$ sensitizes TRPV1-mediated increases in $[Ca^{2+}]_i$ by PKC ϵ - and PKA-dependent mechanisms.

By recording whole-cell currents in HEK-TRPV1 cells, we found that pretreatment with PAR $_2$ -AP (100 μ M) resulted in a threefold increase in the current induced by capsaicin (300 nM) applied 30 s later, indicative of TRPV1 sensitization (Fig. 7A). This sensitization was maximal when capsaicin was applied 3 min after PAR $_2$ -AP when the capsaicin current was increased by 440% ($n = 10$), and sensitization was sustained for at least 18 min (Fig. 7B). Repeated applications of capsaicin alone over the same time period resulted in reproducible responses, with no significant change in magnitude of TRPV1 currents ($n = 5$; data not shown). Thus, TRPV1 did not desensitize in response to repeated challenges with this concentration of capsaicin. When PKC ϵ I (200 μ M) or H-89 (3 μ M) were included in the pipette, they markedly inhibited the PAR $_2$ -mediated sensitization (Fig. 7C). Pretreatment with the PKC agonist phorbol dibutyrate (300 nM) also sensitized TRPV1 currents, causing a fourfold increase in capsaicin-evoked current at 3 min. However, this sensitization was not inhibited by H-89, demonstrating that the effect of H-89 did not result from non-selective inhibition of PKC pathways (phorbol dibutyrate = $429 \pm 126\%$ increase; phorbol dibutyrate + H-89 = $685 \pm 126\%$ increase; $n = 8$). Thus, PAR $_2$ sensitizes TRPV1 currents in HEK-TRPV1 cells by PKC ϵ and PKA-dependent mechanisms.

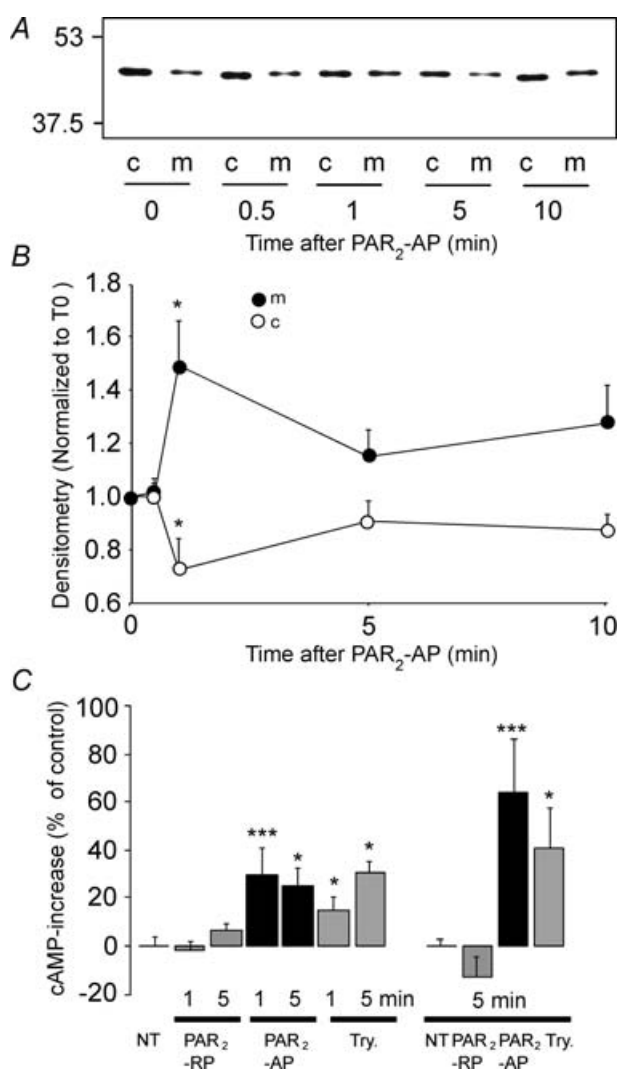


Figure 5. Effects of PAR $_2$ agonists on the subcellular distribution of PKA $_C$ (catalytic subunit) in HEK 293 cells and on cAMP levels. *A*, Western blot, and *B*, densitometric analysis of PKA $_C$ in cytosolic (c) and membrane (m) fractions of HEK-TRPV1 cells. PAR $_2$ -AP caused an increase in PKA $_C$ in membrane fractions and a decrease in cytosolic fractions. * $P < 0.05$ compared to 0 min, $n = 4$ experiments. *C*, effects of PAR $_2$ agonists on cAMP level in HEK-PAR $_2$ cells (left) and DRG neurons (right). Try. = trypsin. PAR $_2$ -AP and trypsin caused an increase in cAMP levels after 1 and 5 min. $n = 3$ experiments. * $P < 0.05$ compared to non-treated cells (NT), *** $P < 0.05$ compared to PAR $_2$ -RP.

PAR $_2$ agonists sensitize TRPV1 to induce thermal hyperalgesia by PKC ϵ - and PKA-dependent mechanisms

We have previously reported that the co-administration of non-algesic doses of PAR $_2$ -AP and capsaicin induces thermal hyperalgesia (Amadesi *et al.* 2004). Antagonism or deletion of TRPV1 prevents this response, indicating that PAR $_2$ sensitizes TRPV1 to cause thermal hyperalgesia.

Using the same experimental approach, we now sought to investigate the role of PKC ϵ and PKA in PAR₂-induced sensitization of TRPV1-dependent thermal hyperalgesia. By measuring the paw withdrawal latency to radiant heat in mice, we found that co-injection of non-algesic doses of PAR₂-AP (1 ng paw⁻¹) and capsaicin (1 μ g paw⁻¹) caused hyperalgesia, as indicated by a decrease in the paw withdrawal latency (Fig. 8A and B). This hyperalgesia was detected within 15 min and sustained for at least 120 min. Thus, as previously reported (Amadesi *et al.* 2004), PAR₂-AP can sensitize TRPV1-induced thermal hyperalgesia. To determine the contribution of PKC ϵ and PKA to this effect, we administered selective inhibitors (Aley *et al.* 2000). Intraplantar injection of PKC ϵ I (1 μ g paw⁻¹), a selective inhibitor of PKC ϵ translocation, alone did not affect the basal withdrawal latency (Fig. 8A). However, PKC ϵ I strongly inhibited the hyperalgesic effect of PAR₂-AP and capsaicin at 15 and 30 min, and abolished hyperalgesia at 60 and 120 min (Fig. 8A). The inactive PKC ϵ I-sc (1 μ g paw⁻¹) had no effect on the response to co-injection of PAR₂-AP and capsaicin (Fig. 8A).

The intraplantar injection of WIPTIDE (1 μ g paw⁻¹), a selective PKA inhibitor, alone had no significant effect on the basal withdrawal latency (Fig. 8B). However, WIPTIDE abolished the hyperalgesic effect of PAR₂-AP and capsaicin at 30–120 min (Fig. 8B). Thus, PAR₂ sensitizes TRPV1 to induce thermal hyperalgesia by a mechanism that requires activation of both PKC ϵ and PKA.

Discussion

It is well established that certain proteases can cleave PAR₂ on sensory neurons to stimulate the release of substance P and calcitonin gene-related peptide, thereby causing neurogenic inflammation and both thermal and mechanical hyperalgesia (Steinhoff *et al.* 2000; Vergnolle *et al.* 2001). It is also known that PAR₂-induced thermal hyperalgesia is dependent on sensitization of TRPV1 (Amadesi *et al.* 2004; Dai *et al.* 2004). However, the molecular mechanisms by which PAR₂ sensitizes TRPV1 to cause thermal hyperalgesia are not fully understood. Our results show, for the first time, that (1) PAR₂ is co-expressed

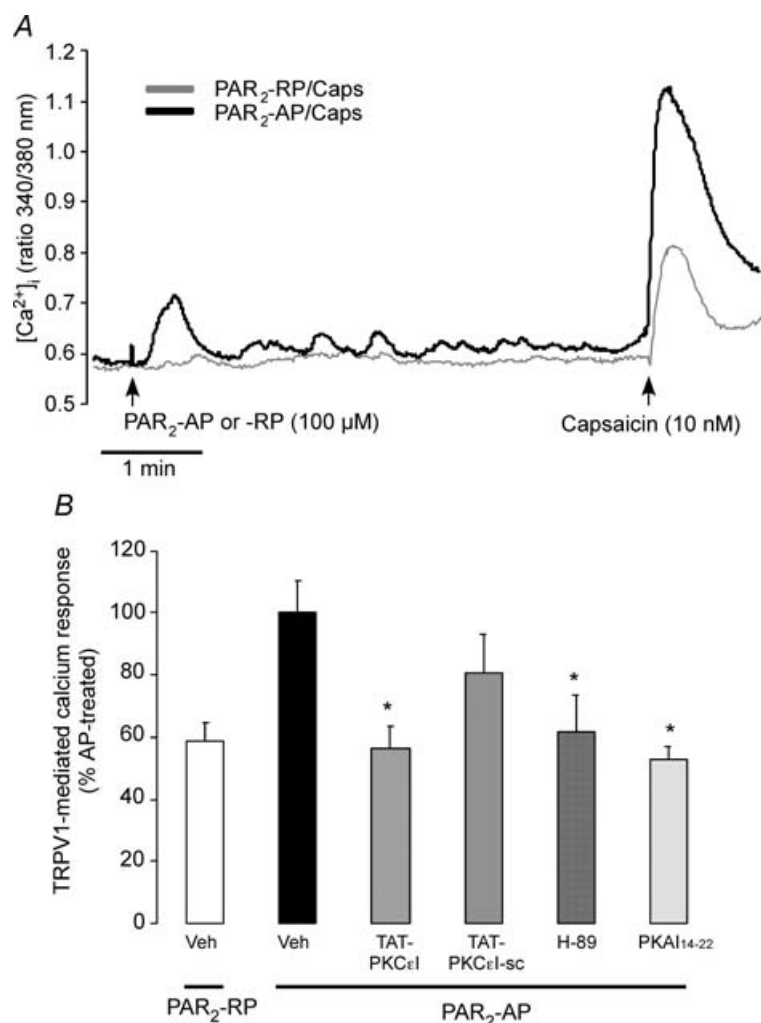


Figure 6. Effects of PAR₂ agonists on capsaicin-induced Ca²⁺ signalling in HEK-TRPV1 cells

Cells were exposed to PAR₂-AP or PAR₂-RP for 5 min, and then challenged with capsaicin. *A*, changes in [Ca²⁺]_i, with each line the average trace from *n* = 31–35 cells. *B*, the effects of antagonists on PAR₂-induced sensitization of capsaicin responses (100%). Veh = vehicle control. **P* < 0.05 compared to PAR₂-AP/vehicle cells. *n* = 70–80 cells from 3 experiments.

with PKC ϵ and PKA in small- and medium-diameter primary sensory neurons that transmit pain; (2) PAR $_2$ agonists activate PKC ϵ and PKA, causing their translocation to the plasma membrane in cell lines and DRG neurons and that PAR $_2$ agonists activate the cAMP/PKA cascade in these cells; (3) activation of PKC ϵ

and PKA is required for the PAR $_2$ -mediated sensitization of TRPV1 Ca $^{2+}$ signals and currents; and (4) PKC ϵ and PKA mediate PAR $_2$ -induced sensitization of TRPV1 *in vivo*, and are thus responsible for the resultant thermal hyperalgesia.

Several observations from the current investigation suggest that PAR $_2$ agonists activate PKC ϵ and PKA. We found that small- to medium-diameter neurons, which are known to express PAR $_2$ and TRPV1 (Amadesi *et al.* 2004), also contain PKC ϵ and PKA. By a combination of confocal microscopy, subcellular fractionation and Western blotting, we observed that PAR $_2$ agonists promoted translocation of PKC ϵ and the catalytic subunit of PKA, which represents the active subunit of the PKA heterotetramer, from the cytosol to the plasma membrane in both DRG neurons and HEK 293 cells. PMA and forskolin, established activators of PKC and PKA, had similar effects on the subcellular localization of these kinases. Thus, translocation of kinases from the cytosol to the plasma membrane can be used in our system as an indicator of kinase activation. Our results show that PKC ϵ and PKA $_C$ are not only appropriately colocalized with PAR $_2$ and TRPV1 in nociceptive neurons, but that PAR $_2$ activates these kinases. Our findings are consistent with other reports of the localization of PAR $_2$, PKC ϵ and PKA $_C$ in primary sensory neurons. PAR $_2$ is expressed by > 50% of small- to medium-diameter neurons of rat DRG (Steinhoff *et al.* 2000), and PKC ϵ is present in 90% (Khasar *et al.* 1999) and PKA $_C$ in 50% (Rathee *et al.* 2002) of these neurons. We found that PAR $_2$ agonists caused redistribution of kinases in ~60% of cells expressing PKC ϵ and in ~80% of cells expressing PKA.

It is well established that PAR $_2$ couples to G $_{\alpha q/11}$, resulting in activation of phospholipase C β and generation of 1,4,5-inositol trisphosphate and diacylglycerol, which would be expected to mobilize intracellular Ca $^{2+}$ ions and activate PKC (Ossovska & Bunnett, 2004). Therefore, PAR $_2$ -induced activation of PKC ϵ is consistent with the known signalling pathway of this receptor. Moreover, our results are in line with observations that agonists of PAR $_2$ induce activation and membrane translocation of PKC ϵ in prostate stromal cells (Myatt & Hill, 2005). Given the predominant coupling of PAR $_2$ to G $_{\alpha q/11}$, the observation that PAR $_2$ agonists caused membrane translocation of PKA $_C$ was unanticipated. However, we observed that PAR $_2$ agonists stimulated generation of cAMP in DRG neurons and HEK 293 cells, suggesting that PAR $_2$ activates the cAMP/PKA cascade. Our results are in agreement with the observations that PAR $_2$ agonists elevate cAMP levels in keratinocytes (Scott *et al.* 2003), and that PAR $_2$ activation causes release of von Willebrand factor in endothelial cells by a PKA-dependent mechanism (Cleator *et al.* 2006). Thus, PAR $_2$, like PAR $_1$, may couple to different heterotrimeric G proteins and thereby regulate multiple signalling pathways, including mobilization of intracellular Ca $^{2+}$ ions and generation of cAMP

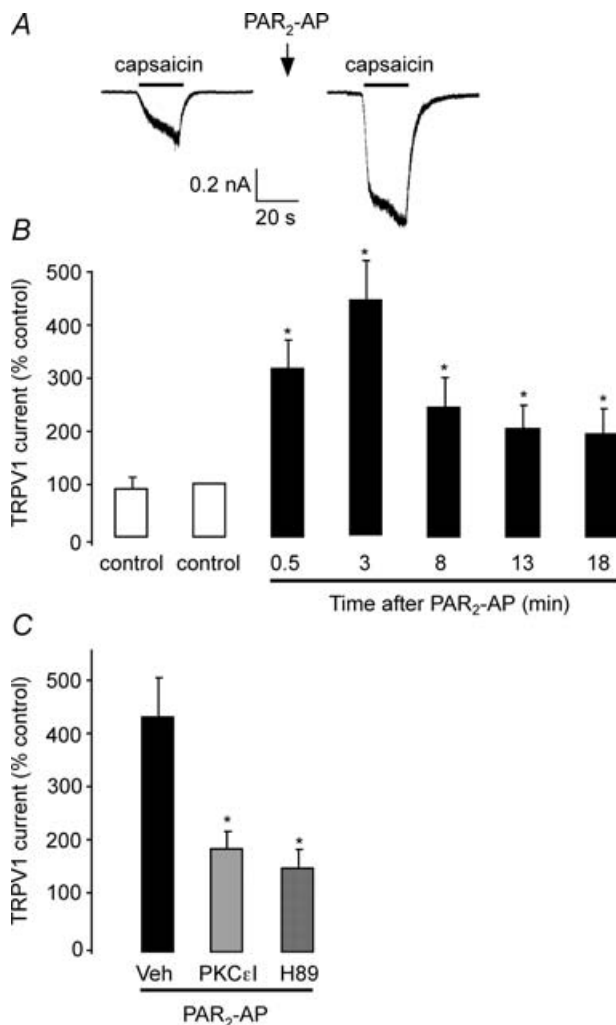


Figure 7. PKC ϵ and PKA antagonists inhibit the PAR $_2$ -mediated sensitization of TRPV1 currents in HEK-TRPV1 cells

A, whole-cell inward currents induced by capsaicin (300 nM) before (left trace) and 3 min after (right trace) application of PAR $_2$ -AP for 2 min. B, summary of mean TRPV1 currents over time following activation of PAR $_2$ with PAR $_2$ -AP (100 μ M; $n \geq 5$ for each time point). PAR $_2$ -AP sensitized the capsaicin-induced current in a time-dependent manner; reaching its maximum value 3 min after PAR $_2$ -AP treatment ($P < 0.01$; $n = 10$). Membrane current values are expressed as percentage of the control current recorded prior to PAR $_2$ -AP application (second control bar). In five control cells (first control bar), capsaicin was applied for ~20 s and re-applied 3 min later (second control bar), demonstrating the consistency of the capsaicin response. In another five control cells, capsaicin was only applied once before application of PAR $_2$ -AP. C, TRPV1 sensitization by PAR $_2$ -AP (Veh = vehicle control $n = 10$, at 3 min) was prevented by PKC ϵ (PKC ϵ I, 200 μ M, $n = 5$) and PKA (H89, 3 μ M, $n = 5$) inhibitors.

* $P < 0.05$.

(Ossovskaya & Bunnett, 2004). Alternatively, PAR₂ agonists could induce release of mediators that act in an autocrine manner to generate cAMP and activate PKA. One possible mediator is PGE₂, since PAR₂ agonists promote PGE₂ release from epithelial cells (Kong *et al.* 1997) and PGE₂ sensitizes TRPV1 through a PKA-dependent mechanism (Lopshire & Nicol, 1998; Rathee *et al.* 2002). However, we found that indomethacin did not prevent the effects of PAR₂ agonists on cAMP generation. Further studies are thus required to determine the mechanism by which PAR₂ agonists activate PKA in neurons.

Upon translocation to the plasma membrane, activated PKC ϵ and PKA may phosphorylate and thereby sensitize ion channels that participate in nociception, such as TRPV1. Several observations from our investigation support this possibility. Firstly, we observed that PAR₂ agonists sensitized capsaicin-induced increases in [Ca²⁺]_i and capsaicin currents in HEK-TRPV1 cells, and we and others have previously reported similar sensitization in DRG neurons (Amadesi *et al.* 2004; Dai *et al.* 2004). Secondly, the co-injection of non-algesic doses of PAR₂ and capsaicin induced sustained thermal

hyperalgesia, which we have shown to depend on sensitization of TRPV1 (Amadesi *et al.* 2004). Finally, selective antagonists of PKC ϵ and PKA, including those that prevent membrane translocation of these kinases, prevented the PAR₂-induced sensitization of TRPV1-dependent Ca²⁺ signalling, TRPV1 currents and TRPV1 thermal hyperalgesia. These results are supported by the observation that PAR₂ agonists phosphorylate TRPV1 in HEK 293 cells (Amadesi *et al.* 2004). Our observation that PKC ϵ makes an important contribution to PAR₂-induced sensitization of TRPV1 is in agreement with the report that PKC ϵ antagonists suppress the effects of PAR₂ agonists on TRPV1 Ca²⁺ signalling and TRPV1 currents (Amadesi *et al.* 2004; Dai *et al.* 2004). However, our results extend this report by showing that PAR₂ activates a specific PKC isozyme, and by demonstrating a major role for both PKC ϵ and PKA in PAR₂-induced thermal hyperalgesia.

The precise signal transduction pathway by which PAR₂ activates PKC ϵ and PKA to sensitize TRPV1 remains to be elucidated. PKC ϵ and PKA can both directly phosphorylate TRPV1 (Bhave *et al.* 2002; Numazaki *et al.* 2002; Mohapatra & Nau, 2003). However, after activation

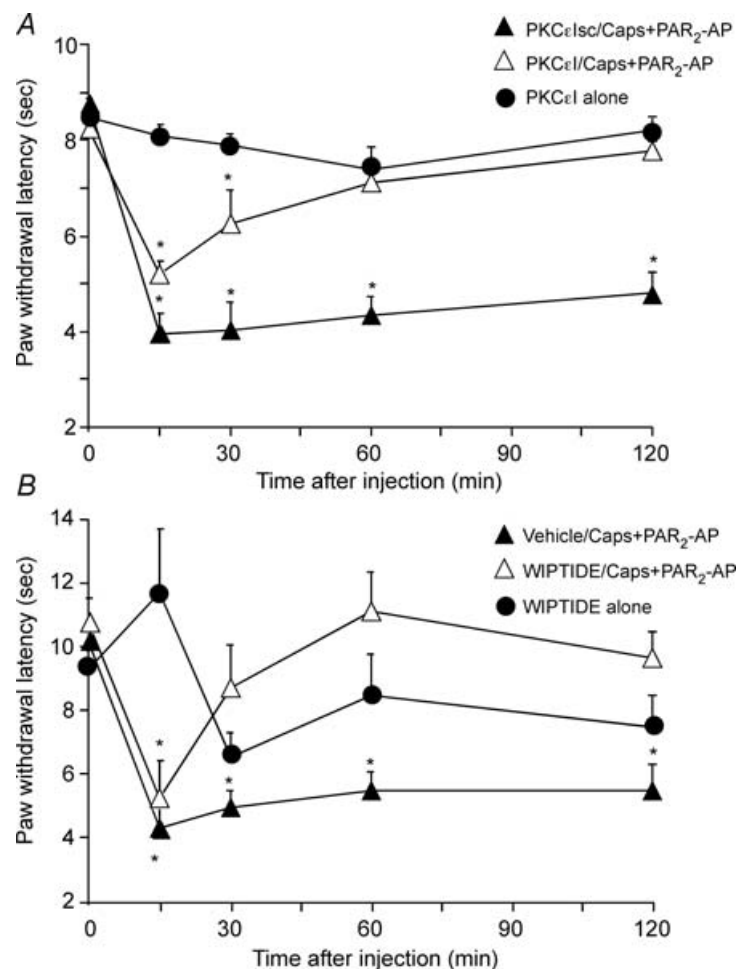


Figure 8. Mechanisms of PAR₂-induced potentiation of TRPV1-mediated thermal hyperalgesia

Compounds were injected into the paws of mice, and hyperalgesia was measured as a significant decrease in withdrawal latency in response to a thermal stimulus, compared to basal (time 0). *A*, effects of the PKC ϵ inhibitor (PKC ϵ I) alone or on PAR₂-AP and capsaicin-induced hyperalgesia. *B*, effects of the PKA inhibitor (WIPTIDE) alone or on PAR₂-AP and capsaicin-induced hyperalgesia. Controls include use of inactive PKC ϵ I-sc or the WIPTIDE vehicle. *n* = 8 mice per group, **P* < 0.05 compared to basal values.

of PAR₂, we do not know if PKC ϵ and PKA regulate TRPV1 in an additive or synergistic manner, or whether one pathway is upstream of the other. When administered separately, we observed that PKC ϵ and PKA inhibitors almost completely prevented PAR₂-induced sensitization of TRPV1 Ca²⁺ signals and currents. Moreover, PKC ϵ and PKA inhibitors both prevented PAR₂-induced thermal hyperalgesia at later times (> 30 min). Together, these results suggest the activation of tandem and possibly redundant PKC ϵ and PKA pathways. However, at earlier times (< 30 min), PKC ϵ and PKA inhibitors, when given separately, did not prevent PAR₂-induced thermal hyperalgesia. Thus, the relative contributions of PKC ϵ and PKA may vary with time after activating PAR₂. This possibility is supported by the identification of a novel cAMP/PKC ϵ signalling pathway that is responsible for the long-lasting latent susceptibility to hyperalgesia induced by an acute inflammatory stimulus (Parada *et al.* 2005) where an upstream release of cAMP and activation of the guanine exchange factor Epac, but not of PKA, are required to activate downstream PKC ϵ (Hucho *et al.* 2005). Although our observations that PKA inhibitors prevented the PAR₂-induced sensitization of TRPV1 suggest a distinct role for PKA, in addition to the contribution of PKC ϵ , further experiments are required to define the relative roles of these kinases at different times after activation of PAR₂.

In addition to the direct phosphorylation of TRPV1 by PKC ϵ and PKA, other mechanisms may account for PAR₂-induced sensitization of this channel. PAR₂ agonists may also activate other second messenger kinases, such as protein kinase D, a substrate for PKC ϵ (Rey *et al.* 2004; Wang *et al.* 2004) that can also phosphorylate and sensitize TRPV1 (Rey *et al.* 2004; Wang *et al.* 2004). Furthermore, PAR₂ agonists could regulate the subcellular distribution of TRPV1 rather than affecting gating of the channel. Indeed, phorbol esters, agonists of the metabotropic glutamate receptor and nerve growth factor sensitize neurons by promoting trafficking of TRPV1 to the plasma membrane (Morenilla-Palao *et al.* 2004; Zhang *et al.* 2005). These possibilities remain to be examined, and the existence of other mechanisms cannot be excluded.

Further studies are required to define the physiological relevance of PAR₂-induced hyperalgesia. In the present investigation, we studied the effects of a synthetic agonist, PAR₂-AP, on thermal hyperalgesia. However, we have previously reported that proteases such as tryptase and trypsin similarly cause hyperalgesia by activating PAR₂ (Vergnolle *et al.* 2001). Agents that degranulate mast cells also induce hyperalgesia by a PAR₂-dependent mechanism (Vergnolle *et al.* 2001). Although tryptase may mediate these effects, experiments with tryptase inhibitors are required to confirm this possibility. Extrapancreatic trypsins, such as trypsin IV, can activate

PAR₂ (Cottrell *et al.* 2004), but their role in pain transmission remains to be defined. In the present study, we observed that PAR₂-AP-induced thermal hyperalgesia was sustained for 2 h, and we have previously reported detectable hyperalgesia 24 h after PAR₂ activation (Vergnolle *et al.* 2001). Although our results suggest that PKC ϵ and PKA account for hyperalgesia at up to 120 min after activation, different mechanisms may mediate hyperalgesia at later times. Proteases activate PAR₂ in a catalytic and irreversible manner; once the receptor is cleaved the exposed tethered ligand is always available to activate PAR₂. Receptor phosphorylation by G protein receptor kinases and interaction with β -arrestins serve to uncouple receptors from heterotrimeric G proteins and desensitize G protein signalling (Bohm *et al.* 1996; Dery *et al.* 1999). However, β -arrestins also mediate receptor endocytosis and are scaffolds for mitogen-activated protein kinases, which permits internalized PAR₂ to continue to signal through this pathway (DeFea *et al.* 2000). The contribution of β -arrestins and mitogen-activated protein kinases to sustained hyperalgesia remains to be defined. Eventually, PAR₂ is targeted for degradation in lysosomes by a ubiquitin-mediated mechanism, which irrevocably terminates signalling (Jacob *et al.* 2005). In cell lines, resensitization of responses to proteases requires synthesis of new receptors and mobilization of prominent stores of PAR₂ from the Golgi apparatus. We have shown that PAR₂-AP causes redistribution of β -arrestin1-EGFP from the cytosol to the plasma membrane, followed by translocation of PAR₂-EGFP and β -arrestin1-EGFP from the plasma membrane to endosomes of DRG neurons (S. Amadesi & N. W. Bunnett, unpublished observations). However, the mechanisms of resensitization of PAR₂ in neurons, which may be required for the sustained hyperalgesic effects of PAR₂ agonists, are completely unknown.

Together, our results further clarify the signalling pathways by which PAR₂ regulates TRPV1 to induce hyperalgesia. We used a combination of experimental approaches, including localization of kinases in DRG, analysis of the subcellular distribution of PKC ϵ and PKA_C, measurement of TRPV1 mediated Ca²⁺ signalling and currents, and behavioural studies in conscious animals, to reveal a major role of PKC ϵ and PKA in PAR₂ signalling and PAR₂-induced sensitization of TRPV1. An understanding of the mechanisms by which proteases that activate PAR₂ sensitize ion channels such as TRPV1 is important for the development of novel therapies to treat pain.

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